MAGNETIC PROPERTY CHANGES IN VARIOUS STRUCTURAL STEELS DUE TO IRRADIATION

M.K. Devine, D.C. Jiles
Center for NDE
Ames IA 50011

P.K. Liaw, R.D. Rishel, D.S. Drinon
Westinghouse Electric Corporation
1310 Beulah Road
Pittsburgh, PA 15235

INTRODUCTION

Nondestructive evaluation in nuclear power plants has been a growing concern for electric utility operators over the past decade1. Many plants are operating beyond their original design lives primarily through intermittent replacement of individual components as necessary. It is critically important for the NDE field to develop technology that can evaluate the life expectancy of components in these plants, such as steam boiler pipes, headers and tubes, steam turbine rotors and blades, and nuclear pressure vessels. These components typically experience long service exposure, high temperature under high loading conditions, corrosive media and neutron irradiation. The focus of this paper will be on the irradiation effects.

During irradiation, the following effects have been found to occur: an increase in the yield stress, an increase in hardness, an decrease in work hardening rate, a decrease in ductility, an increase in ductile-to-brittle-transition-temperature (DBTT) and a decrease in the upper shelf energy. These effects are illustrated in figures 1 and 2. The weldment connecting pipes and pressure vessels is a radiation sensitive component in nuclear power plants. Most weldments contain copper to facilitate the welding process and copper plays a significant role in the embrittlement process. Copper precipitates can cause hardening and embrittlement by impeding dislocation movement. This paper will describe an investigation performed to determine irradiation effects on ASTM A533-B material and weldments containing various amounts of copper.

MATERIALS AND EXPERIMENTAL PROCEDURE

Samples tested for this investigation were broken and unbroken Charpy specimens of ASTM A533-B material containing welds. The samples were welded using the submerged arc process and the Charpy specimens were machined so that the weld was in the middle of the Charpy as shown in figure 3. Three weldments with copper content varying from 0.234 wt% to 0.385 wt% were used. Table 1 shows the various copper contents and specimen designations used throughout this investigation. The irradiation process consisted of exposing

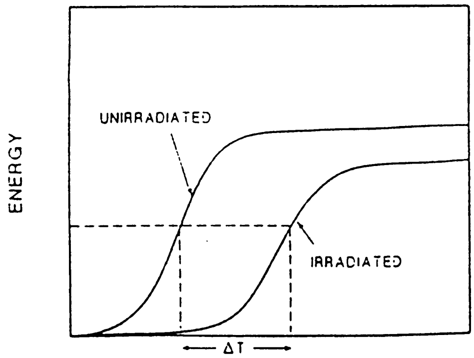

Figure 1 Plot of impact energy vs. temperature from a Charpy test. Note how the irradiated specimens absorb less energy at all temperature. The rapid decrease in energy reflects the transition to brittle behavior.

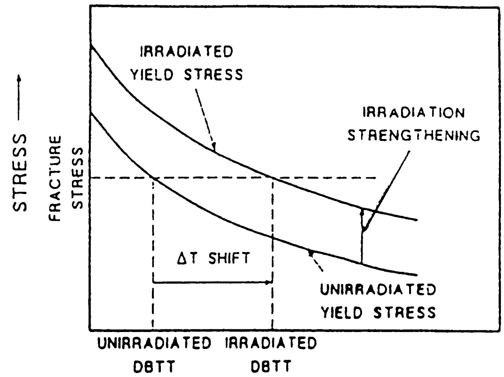

Figure 2 Plot showing the increase in yield strength produced by irradiation.

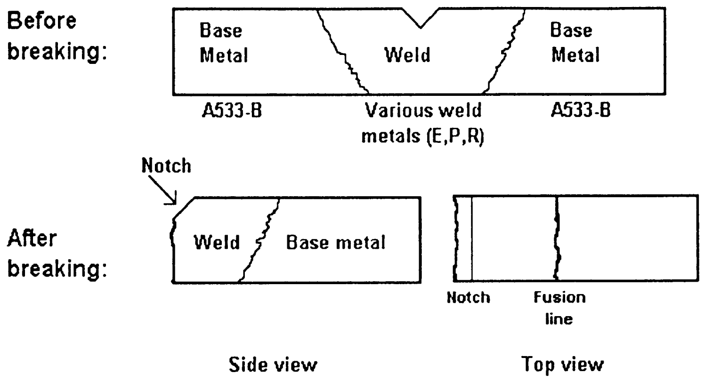

Figure 3 Orientation of the weld in the Charpy specimen.

the Charpy specimens to a neutron flux at fluences of either 8.4 x 10^{18} n/cm^2 or 15x10^{18} n/cm^2. The samples were removed and most were annealed at 850°F (454°C) for 168 hours. The remainder were left in the irradiated state. A portion of the annealed specimens were irradiated again, this time at a fluence of 7.7 x 10^{18} n/cm^2. Following this, a portion of these irradiated specimens were annealed at 850°F (454°C) for 168 hours, the remainder were left irradiated. These samples were intended for an irradiation-aging experiment and thus the impact tests had been performed over a wide range of temperatures. Due to the destructive nature of the test, it was decided that magnetic measurements would be limited to specimens broken at a temperature below 0°C. These samples had broken in a brittle manner and thus there was minimal plastic deformation.

Magnetic measurements were made by a device called the Magnescope[2] on the Charpy specimens. Two different sized inspection heads were used, a medium inspection head which would incorporate measurement of weld and base material simultaneously (see figure 4a) and a small inspection head which could take separate readings on the base and the weld material (see figure 4b). The notch side of the specimens was chosen because it was believed that this side would have received the least amount of plastic deformation.

Eddy current measurements had also been performed on these specimens. The eddy current probe was small enough to take separate weld and base measurements.

Table 1

Sample ID	Irradiation history	Charpy Temp	Charpy Energy (ft-lb)
E343	Unirradiated, annealed 454° C*	-73° C	9.5
E240	Irrad @ $15x10^{18}$ n/cm^2	-18° C	3
E074	Irrad @ $8.4x10^{18}$ n/cm^2, annealed 454° C*	-73° C	7
E217	Irrad @ $15x10^{18}$ n/cm^2, annealed 371 ° C*	-73° C	4
P327	Unirradiated, annealed 454° C*	-18° C	25.5
P036	Irrad @ $8.4x10^{18}$n/cm^2	0° C	5.5
P071	Irrad @ $8.4x10^{18}$ n/cm^2, annealed 454° C*	-46° C	20
P224	Irrad @ $15x10^{18}$n/cm^2, annealed 371° C*	-77° C	5
P151	Irrad @ $8.4x10^{18}$ n/cm^2, annealed 454° C*, reirradiated $7.7x10^{18}$ n/cm^2	-46° C	16.5
R342	Unirradiated, annealed 454° C*	-46° C	71.5
R236	Irrad @ $15x10^{18}$ n/cm^2	-18° C	15
R005	Irrad @ $8.4x10^{18}$ n/cm^2, annealed 454° C*	-46° C	8
R219	Irrad @ $15x10^{18}$ n/cm^2, annealed 371° C*	-77° C	8
R151	Irrad @ $8.4x10^{18}$ n/cm^2, annealed 454° C* reirradiated $7.7x10^{18}$ n/cm^2	-77° C	7.5

* All annealing was done for 168 hours

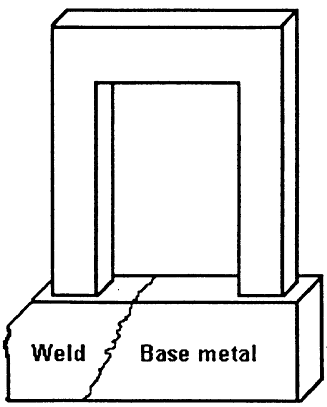

Figure 4a Orientation of the medium inspection head on a Charpy specimen.

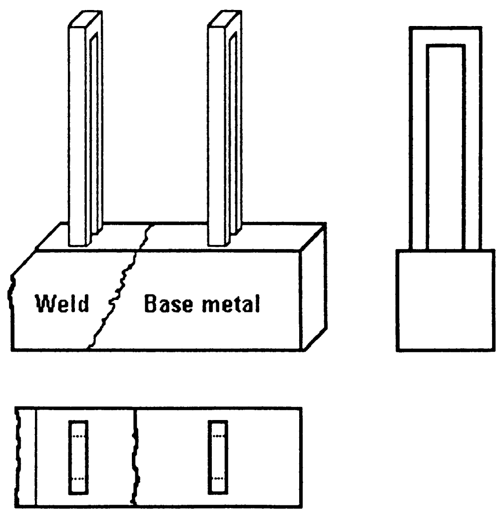

Figure 4b Orientation of the small inspection head on a Charpy specimen.

RESULTS AND DISCUSSION

Figure 5 shows the results of an eddy current inspection, performed on Charpys with EP-23 weldment, in the untreated, irradiated and irradiated & annealed condition. As can be seen, the eddy current signature decreased for both the weld and the base material after irradiation. Samples that were irradiated & annealed however, increased almost to the levels of the untreated specimens.

Figure 6 shows the results from using the medium inspection head on the weldment samples. All three groups of weldments are shown. These measurements consisted of simultaneous measurements on the weld and base material. As can be seen, there is a decrease in the coercivity in all the samples that were irradiated except for one in the E group. Samples that were irradiated & annealed did not have significantly different coercivities compared with the irradiated-only samples.

Figure 7 shows the remanence measurements on the same group of specimens. The remanence of the irradiated-only group decreased relative to the unirradiated group. Only some of the irradiated & annealed samples showed increases in remanence, when compared with the irradiated samples. At this time it is not entirely clear what mechanism is reducing the coercivity and remanence with irradiation.

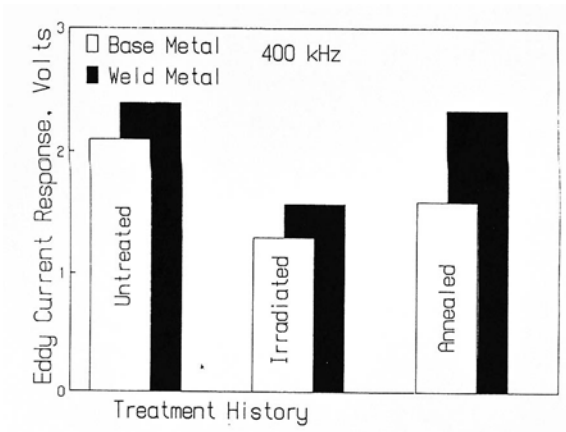

Figure 5 Eddy current results. Voltage response decrease on irradiated specimens (in both the base and weld metal region) and increased to near untreated levels on the annealed specimen.

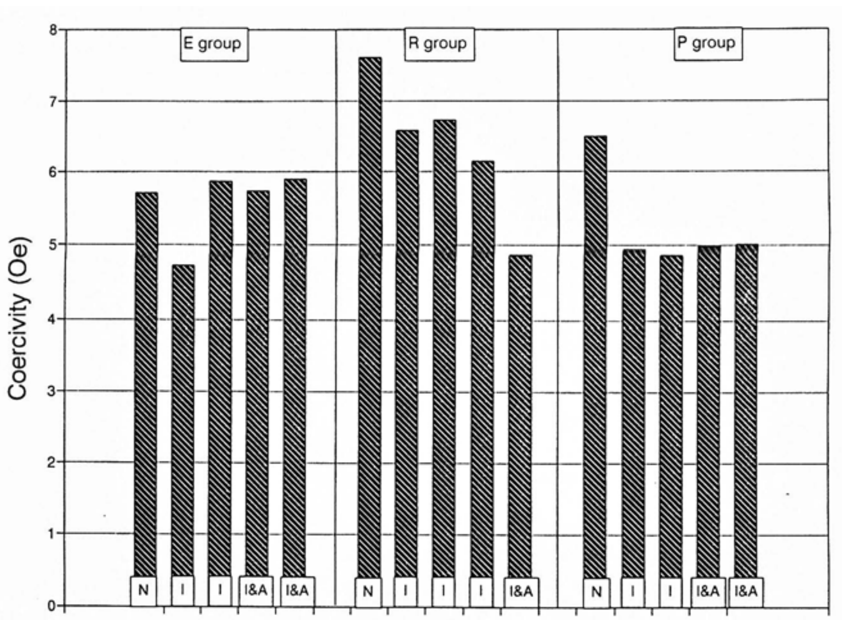

Figure 6 Magnetic hysteresis results. Coercivity of weld/base combined (used medium inspection head).

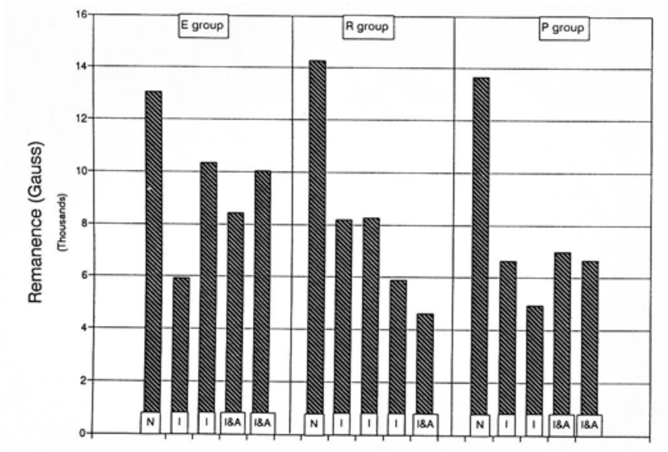

Figure 7 Magnetic hysteresis results. Remanence of weld/base combined (used medium inspection head).

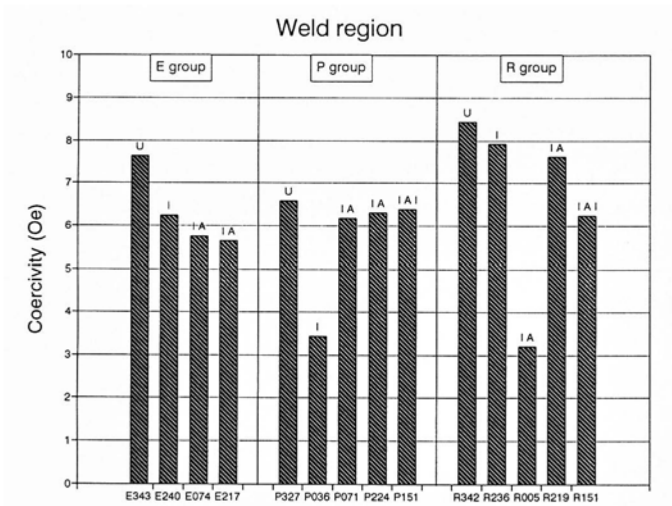

Figure 8 Coercivity of weldment portion of Charpy specimens.

The next step in this investigation consisted of using a small inspection head to take separate weldment and base measurements on these Charpy specimens. Figure 8 displays the coercivity measured on the weldment portion of the Charpy specimens. In every group, the coercivity of the irradiated specimens (E240, P327, R236) was significantly below the coercivity measured on the corresponding unirradiated specimens (E343, P327, R342). This is consistent with observations in combined weld and base measurements (figure 6). Since these are Charpy specimens, it is theorized that the irradiation is promoting brittle fracture, minimizing the damage that would occur in a specimen. The less damage to the specimen, the less the coercivity. It is strongly believed that this irradiation effect would be detected in unbroken Charpy specimens. Sample P036 (irradiated) had a coercivity that was 3 Oe lower than P327 (unirradiated). Such a large difference was probably due to the much higher temperature at which P036 was broken (25°C). The effect of annealing on the weld is not clear. In the E group, the annealed specimens (E074, E217) had coercivities smaller than the irradiated specimen. In the P group, the annealed specimens (E071, P224) had much higher coercivities than the irradiated specimen. The R group had one specimen with a smaller coercivity (R005), another specimen with a higher coercivity (R219). The absence of a trend could possible be due to the different alloy composition in the weld and the resultant differing responses to irradiation. But again, this is not clear. In every case, the irradiated & annealed specimens had coercivities lower than the unirradiated specimens. We are led to believe that the annealing does not affect the magnetic signature after irradiation.

Figure 9 shows the coercivity measured on the base metal portion of the Charpy specimens. The unirradiated specimens of the three groups (E343, P327, R342) all have approximately the same coercivity. This would be expected since the base metal was similar for all three. The irradiated specimens from the E and P group (E240, P036) had reduced coercivities compared with the corresponding unirradiated specimen as was seen in weldments. Curiously, the irradiated specimen from the R group (R236) had a higher coercivity than its corresponding unirradiated specimen (R342). It is not certain why this happened.

Most of the specimens that were irradiated & annealed had a coercivity of 7.7 Oe. This uniformity would be expected due to the similarity of the base material. It is not known why sample P224 had such a small coercivity. The two samples that underwent the cycle of irradiation-annealing-irradiation (P151, R151) had slightly reduced coercivities. This concurs with the trend of a reduced coercivity after irradiation. The base metal coercivity changes are believed to be due to the same mechanism affecting the weld metal.

The remanence results are shown in figure 10. In every group, the irradiated specimens (E240, P036, R236) had a smaller remanence than the unirradiated specimens. In most instances, the irradiated and annealed specimens had remanences larger than the irradiated specimens, almost back up to the unirradiated levels. These trends are similar to what was seen in the coercivity measurements.

Figure 11 shows the remanence measured in the base metal. The unirradiated sample from the E group (E343) had a remanence of about 1900 Gauss whereas the other unirradiated specimens both shared remanences of just under 1600 Gauss. This disparity was not expected since the coercivities of the unirradiated specimens were similar. We have no explanation for this occurrence.

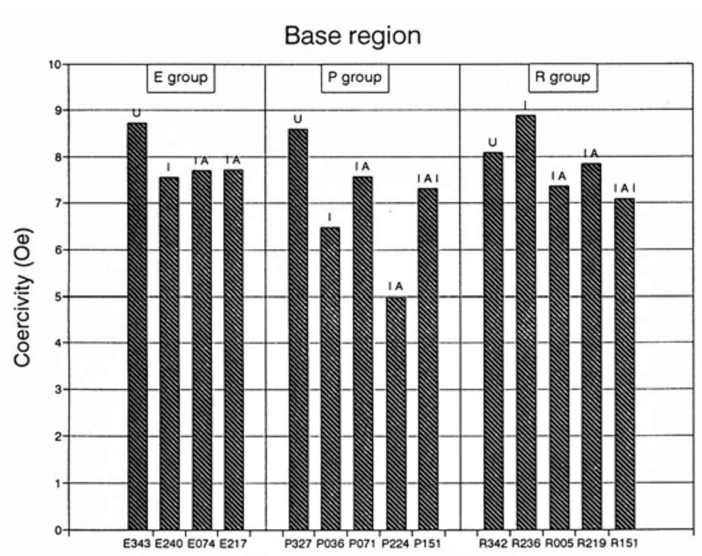

Figure 9 Coercivity of base metal portion of Charpy specimens.

Trends with irradiation and annealing can not be found in the remanence measurements. The irradiated sample in the E and P group (E240 and P036) both decrease relative to the unirradiated sample but this is not true for the R group. Some of the irradiated and annealed specimens have higher remanences than the corresponding irradiated specimens (E074, P071 are examples), a trend seen in the coercivity measurements but other irradiated and annealed specimens have even further reduced remanences. We can only conclude that the remanence is not a strong indicator of irradiation damage in the base metal.

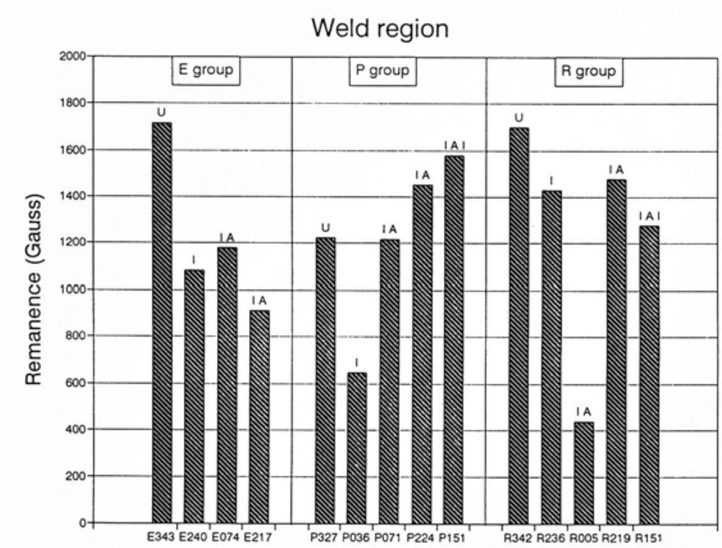

Figure 10 Remanence of weldment portion of Charpy specimens.

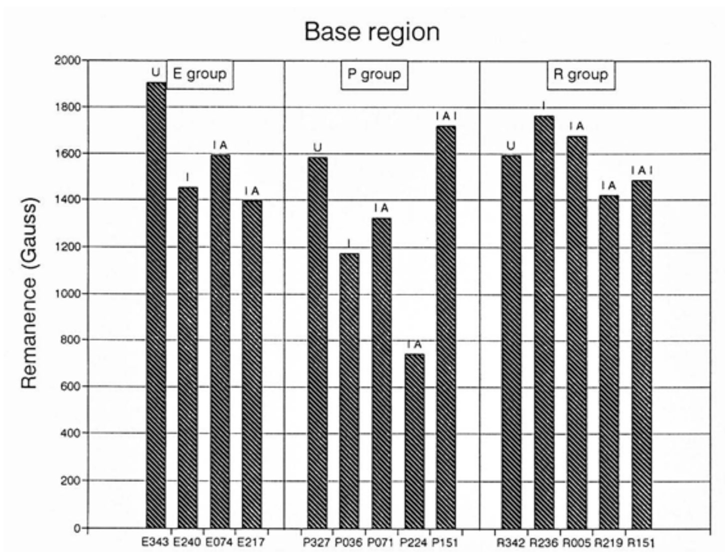

Figure 11 Remanence of base metal portion of Charpy specimens.

CONCLUSIONS

The magnetic properties of both the weld and base region of broken Charpy specimens were found to change with irradiation. Samples of irradiated & annealed material were seen to have magnetic parameters closer to the unirradiated group than the irradiated group, reflecting the effect of annealing. The weld portion showed greater magnetic sensitivity to irradiation and annealing. It was apparent from the results that the coercivity was better able to distinguish between irradiated and unirradiated specimens. The remanence was partially successful in detection of irradiation in weld metal but not in the base metal.

ACKNOWLEDGEMENT

This work was supported by the NSF Industry/University Center for NDE at Iowa State University.

REFERENCES

1. P.K. Liaw, "Commentary: Life prediction technology for aging plants and structural components", JOM, 44(#2), Feb '92, p. 32.
2. D.C. Jiles, S. Hariharan, and M.K. Devine, IEEE Trans. Mag., 26 (1990), p. 2577.
3. J.F. Stubbins, private communication.
4. M.J. Sablik, H. Kwun, G.L. Burkhardt, and D.G. Cadena, to be published in Review of Progress in Quantitative Nondestructive Evaluation, Vol. 12, ed. by D.O. Thompson and D.E. Chimenti (New York, Plenum Press, 1993).